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Metastable electron traps and two-level systems are common in solid-state devices and lead to background charge movement and charge noise in single-electron and single-Cooper-pair transistors. We present measurements of the real-time capture and escape of individual electrons in metastable trapped states at very low temperatures, leading to charge offsets close to 1*e*. The charge movement exhibits thermal excitation to a hysteretic tunneling transition. The temperature dependence and hysteresis can be explained by the coupling of a two-level system to a quasiparticle trap.

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The detection and control of localised electrons in both intrinsic and fabricated traps in solid-state devices are major technical challenges. Single-electron transistors (SET) and single-Cooper-pair transistors (SCPT) are used as sensitive electrometers in charge qubits[1,2], quantum dots[3] and Cooper-pair boxes[4]. But these devices exhibit intrinsic charge traps and two-level systems[5,6,7,8], giving charge offsets, two-level fluctuators, hysteresis and $1/f$ noise[9], which limit their performance. Trapped electrons can escape from a metastable quantum state by tunneling[10] through a potential barrier or thermal activation over the barrier at a temperature T. The escape rate is then proportional to $\exp(-E/kT)$ with activation energy E. In some systems, the potential barrier can be driven to zero[11] by an external control parameter v with $E \propto v^{\xi}$ and $\xi \geq 1$. Trapped electrons can also escape by phonon-assisted tunneling, or tunneling from thermally excited energy levels[12]. We now present measurements of the detailed dynamics of the capture and escape of individual electrons in metastable trapped states at very low temperatures in an SCPT. Individual electron transitions were detected and measured.

The devices, designed for applications in surface-state charge detection[13], were fabricated with multiple metallic layers using e-beam lithography on a Si/SiO_2 substrate. Voltages applied through low pass filters and a 1 m length of thermocoax to a set of gate electrodes controlled the electrostatic potential of an Al-AlO_x-Al SET[14], Figure 1(a). The source-drain current I_{SD}, measured with a DL1211 current preamplifier, exhibited a Josephson-quasiparticle tunneling (JQP) peak and a dissipative Josephson branch, Figure 1(b). Coulomb blockade oscillations (CBO) were observed in I_{SD} when sweeping a gate voltage V_G, due to capacitive coupling C_G to the SET island inducing a charge $Q = -C_G V_G$. On the JQP peak, the CBO were periodic in $Q = 1e$, Figure 1(c). At small source-drain voltages ($V_{SD} < 25$ μV), large amplitude CBO (> 400 pA) were $2e$ periodic[15], Figure 1(c), when the superconducting island was in an even-parity state with no unpaired electrons[16]. The $2e$ CBO amplitude decreased above 250 mK, changing to $1e$ periodicity, due to thermally excited quasiparticles[16]. The low noise CBO ($5 \times 10^{-4}\ e/\sqrt{\text{Hz}}$ at 100 Hz) were stable for long periods. The gate electrodes G1 were strongly coupled with a $1e$ CBO period of 6.6 mV, while gate electrode G2 was weakly coupled with a period of 32.8 mV.

The source-drain current I_{SD} exhibited sudden jumps, equivalent to CBO phase discontinuities, Figure 1(c), for both 1*e* and 2*e* oscillations induced by each of the gates, indicating sudden charge offsets. Over a large G1 sweep of 1500 mV, up to 14 jumps occurred, with a distribution of charge offsets δQ from 0.80*e* to 1.00*e* and a mean of 0.90*e*. Beyond each transition, the CBO were again stable until the gate voltage was reversed, and the charge offset was reset, though with some hysteresis. Small charge offsets, $|\delta Q| < 0.2e$, were sometimes observed but were not reproducible. Each reversible pair of transitions corresponds to electron capture and escape from a trap close to the SET island. In the low temperature limit, there is a threshold voltage V_+ for electron capture (sweeping one gate voltage V_G positive, with other electrodes constant) and a different threshold V_- for electron escape (sweeping V_G negative). The control parameters for each transition are $v_+ = V_G - V_+$ and $v_- = V_- - V_G$, as V_G is swept. Hence $v < 0$ corresponds to voltages before the threshold is reached and $v > 0$ to voltages beyond the threshold. The hysteresis for each pair of transitions is $\Delta V_\pm = V_+ - V_-$. One specific transition was stable and reproducible, enabling detailed measurements of its dynamics.

We measured the real-time capture and escape rates, one electron at a time, by rapidly changing the gate voltage V_{G2} from below the threshold ($v << 0$, stable initial state) to a constant value V_{G2} above the threshold ($v > 0$, the now metastable initial state decays) and then measuring the time before the trap filled or emptied, as seen by a jump in I_{SD}. The trap was reset by sweeping V_{G2} back to the stable state below the threshold. The measurement was repeated to generate an ensemble of switching times t_i (i = 1 to 1000). A plot of the remaining number of initial states versus t_i gives a good exponential $\exp(-t/\tau)$ with a decay time τ, Figure 2. We plot $1/\tau$ versus the gate voltage V_{G2} at 25 mK, in both the electron capture and escape regions. Hysteresis occurs between V_- and V_+, with no charge movement ($1/\tau = 0$). The data is asymmetric. A region of constant $1/\tau$ occurs on both sides of the hysteresis region (dashed lines), but then $1/\tau$ increases rapidly.

We also swept V_{G2} through the threshold at a constant rate $dV_{G2}/dt = \pm a$ and measured the distribution of voltages at which 1000 individual transitions occurred, for a range of temperatures. Figure 3(a) shows the probability $P(v,T)$ of the occupancy of the initial state which decreases from 1 to 0 through the transition. The transition has a sharp threshold at low temperatures and broadens as T increases. The rate of decrease of P is $(1/P)\mathrm{d}P/\mathrm{d}t = a\ \mathrm{dln}P/\mathrm{d}v = -1/\tau$. The slope of the $\log_{10}P$ vs. v plot, Figure 3(b), is proportional to $1/\tau$, and is constant for $v > 0$, above the threshold. Below the threshold ($v < 0$) an Arrhenius factor[9] gives an excellent account of the escape and capture rates as the excitation energy $E = e|v|/\gamma$ increases linearly from zero, where γ is a geometrical voltage scaling factor[17]. Experimentally, an excellent fit is found for

$$1/\tau(v, T) = (1/\tau_0)\exp(-E/kT) \qquad \text{for } v < 0 \qquad (1a)$$

$$1/\tau(v, T) = 1/\tau_0 \qquad \text{for } v \geq 0 \qquad (1b)$$

where $1/\tau_0$ is the value at and above the threshold, which can be integrated to give $P(v,T)$:

$$P(v, T) = \exp[(-\gamma kT/ea\tau_0)\exp(ev/\gamma kT)] \qquad \text{for } v < 0 \qquad (2a)$$

$$P(v, T) = \exp(-\gamma kT/ea\tau_0)\exp(-v/a\tau_0) \qquad \text{for } v \geq 0 \qquad (2b)$$

Fits to Eq.(2) are plotted in Figures 3(a) and (b)[18]. The nested exponentials in Eq.2(a) give a strong temperature dependence for $v < 0$. A plot of $\log_{10}(-\log_{10}P)$ versus v gives a straight line with a slope proportional to $1/\gamma T$. The experimental temperature dependence of γT is shown in Figure 4. Above 50 mK, γT is proportional to T with $\gamma = 145 \pm 5$. Below 50 mK, γT lies above this line, as the electronic temperature of the SET reaches a minimum value (~35 mK) due to Joule heating[19]. The large value for γ reflects the weak coupling of the gate to the small dipole moment of the charge excitation. The escape time $\tau_0(T)$ is almost independent of temperature, Figure 4, and is long, $\approx$ 34 ms, suggesting that the threshold is the onset of energetically allowed tunneling. Similar results are obtained from both parts of the hysteretic transition. By comparison, Buehler *et al.*[20] measured the telegraph noise for a two-level fluctuator in an *rf*-SET with a switching time of 3.4 μs.

Consider first the magnitude of the charge offsets. A 1*e* charge shift corresponds to a parity shift in the superconducting island. But the charge shifts were not precisely 1*e*. The jumps in Figure 1(c) are $0.92 \pm 0.02\ e$. The sign of the induced charge is equivalent to an excess electron brought close to the island, inducing a reduced positive charge $\delta Q = c_1 e/(c_1 + c_2)$ where c_1 and c_2 are the capacitive couplings of the electron to the SET island and elsewhere. If we used only the 1*e* CBO, Figure 1(c), as in previous experiments[6,7], we would wrongly interpret the jump size as $-0.08e$. Random 1*e* jumps were observed previously in an NSN device[21], and were interpreted as the tunneling of electrons from the superconducting SET island to nearby traps. We conclude that there are quasiparticle traps close to the SET island, whose occupancy is limited by Coulomb blockade.

Furlan and Lotkhov[6] investigated intrinsic charge noise in a normal state Al SET on oxidised Si and found bistable traps close to the SET island. Brown, Sun and Kane[7] suggested that small isolated Al grains could act as quasiparticle traps. Fewer charge offsets are observed in a doped silicon SET[22], with no metallic electrodes. Other traps or two-level systems may be associated with chemisorbed oxygen ions or oxygen clusters[23] in the amorphous AlO_x layer.

The temperature dependent tunneling rate is revealing. Tunneling from a superconductor to small metallic particles was studied by Zeller and Giaever[24] and through individual Al particles by Ralph, Black and Tinkham[25]. The tunneling rate $1/\tau$ versus voltage is proportional to the superconducting density of states, and diverges at the energy gap. If the transitions in Figure 3 are tunneling to or from the superconducting island, then we should observe a maximum of $1/\tau$ for $v \geq 0$, rather than the constant $1/\tau_0$. However, Eq.(1) was used by Rogers and Buhrman[9] and by Grupp *et al.*[5] for the relaxation of an intrinsic two-level system (TLS).

We suggest the following to explain (i) charge offsets close to $1e$, (ii) hysteresis and (iii) Arrhenius excitation. As any gate voltage V_G is swept, intrinsic TLS transitions will occur, with local charge movements[6], but relatively small charge offsets, $|\delta Q| < 0.1e$. But each transition will change the Coulomb energy of other nearby traps and may trigger the tunneling of an electron between the SET island and a quasiparticle trap[26], which may then stabilise the TLS, giving hysteresis. The excitation energies[24] of the TLS, E, and the trap, E_1, will depend on V_G, the TLS state ($M = 0, 1$) and the trap occupancy ($N = 0, 1$) as

$$E = e(V_+ - V_G)/\gamma - N\Delta E \tag{3a}$$

$$E_1 = e(V_1 - V_G)/\gamma_1 - M\Delta E \tag{3b}$$

where γ_1 is a voltage scaling factor for the trap as V_G is swept and ΔE is the difference of the Coulomb interaction energy between an electron in the trap and an electron in the $M =$ 0 and the $M = 1$ TLS states. As V_G is swept, the trap will fill, or the TLS switch, whenever E or $E_1 = 0$, or thermal excitation occurs. Since both mechanisms are independently thermally excited, the sequence of events will depend on their relative energies and rates. If we start in the state ($M = 0$, $N = 0$) and sweep V_G positive, the TLS will switch at V_+ to state (1, 0). If this then makes $E_1 < 0$, the trap will rapidly fill ($<< \tau_0$) to state (1, 1), giving $|\delta Q| \approx 1e$, but also decreasing E and stabilising the TLS. Sweeping V_G back negative, the TLS switches to state (0, 1) at V_-, triggering the trap emptying back to (0, 0). The voltage hysteresis $\Delta V_{\pm} = \gamma\Delta E/e$. Thermal excitation will occur as a threshold is approached. A larger change in the gate voltage (Figure 2) may allow the trap to fill without triggering by the TLS. Other charge movements can also affect $\tau_0(T)$ and the threshold voltages. Further details will be given elsewhere.

In summary, the capture and escape of trapped electrons in an SET show charge offsets close to $1e$, thermal excitation to a tunneling transition and hysteresis between metastable states. We suggest that both quasiparticle traps and two-level systems contribute to intrinsic charge movement in SCPTs, and that electrostatic coupling between traps can produce correlated charge movements and hysteresis. This model is consistent with, and could help to explain, previous experiments[6,7].

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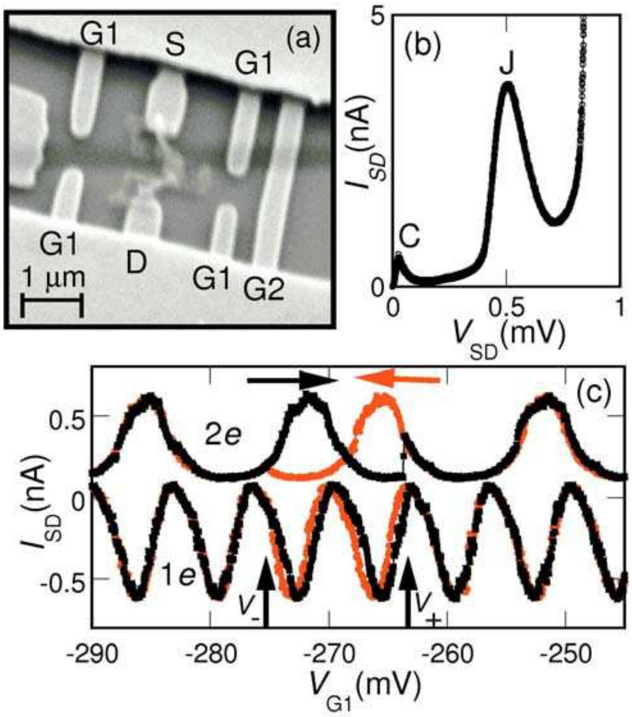
FIG. 1. (Color online) (a) SEM micrograph showing the SET electrodes and island. The source (S), drain (D) and gate (G1, with 4 connected electrodes, and G2) leads are covered by a metallic ground plane. (b) The *I-V* characteristic, showing the Cooper pair peak (C), the JQP peak (J) and the quasiparticle branch. (c) CBO at 15 mK for up (black, ■) and down (red/grey, ●) gate sweeps at the JQP peak (V_{SD} = 0.55 mV, lower trace) showing 1*e* periodicity and at the Cooper pair peak (V_{SD} = 25 µV, upper trace) showing 2*e* periodicity. The data show a hysteretic transition into a trapped charge state with δQ = 0.92 *e*.

FIG. 2. Capture and escape rates 1/τ versus gate voltage V_{G2} at 25 mK. The hysteresis region (A) from -19 to + 37 mV is shown as 1/τ = 0. [Inset: Typical exponential decays into and out of a trap for V_{G2} = 88 mV (In jump, τ = 41.2 ms) and V_{G2} = -88 mV (Out jump, τ = 65.5 ms)].

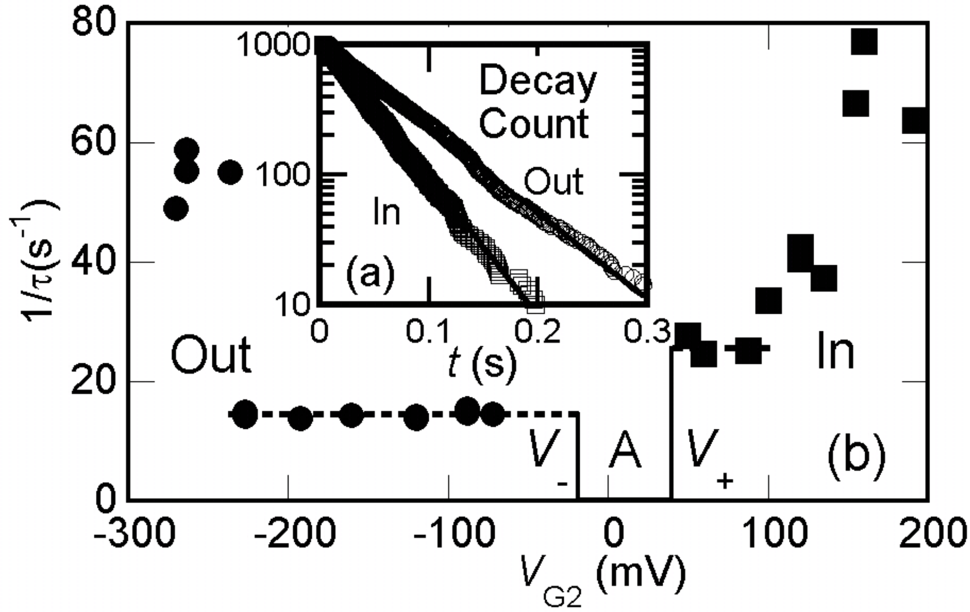
FIG. 3. (Color online) Electronic transitions when sweeping the gate voltage at *a* = 0.036 V/s. The arrow shows the sweep direction. (a) the occupancy of the initial state $P(v, T)$ at 25 mK (○) and 165 mK (□). (b) Logarithmic plots of $P(v, T)$ and $-\log_{10}P(v, T)$ showing the double exponential growth of thermal excitation below the transition (v < 0) and the exponential decay above the transition (v > 0). Lines show fits to Eq.(2).

FIG. 4. The parameters γT(●) and $\tau_0(T)$ (▲) versus the refrigerator temperature *T*. The lines show γT (solid) and γT_{SET} (dotted, allowing for heating[19]) for γ = 145.



G1
S
G1
(a)
G1
D
G1
G2
1 μm
(b)
J
C
I_{SD}(nA)
V_{SD}(mV)
5
0
0
0.5
1
(c)
2e
1e
V_-
V_+
I_{SD}(nA)
0.5
0
-0.5
-290
-280
-270
-260
-250
V_{G1}(mV)

Figure 1



80
60
40
20
0
$1/\tau(s^{-1})$
-300
-200
-100
0
100
200
V_{G2} (mV)
Out
In
V_-
A
V_+
(b)
1000
100
10
0
0.1
0.2
0.3
t (s)
Decay Count
Out
In
(a)

Figure 2

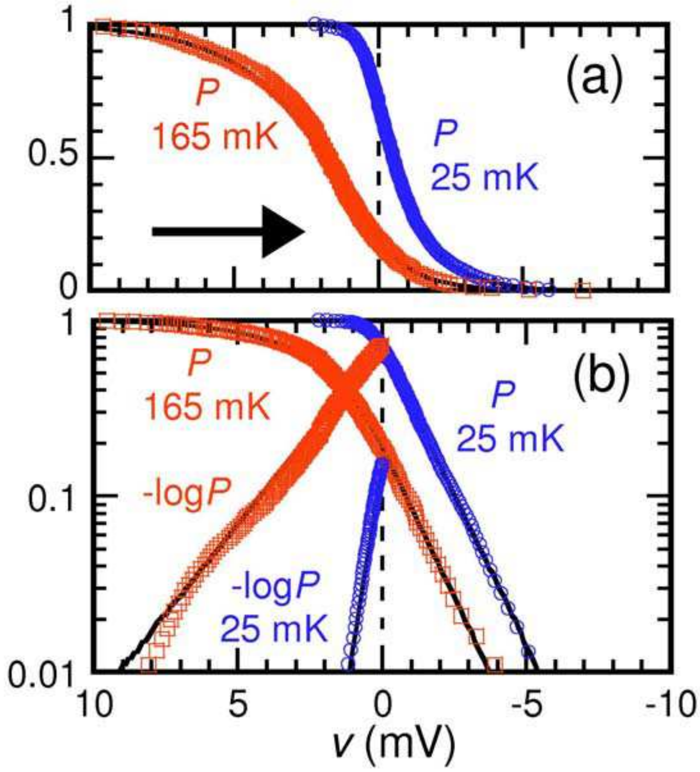


Figure 3

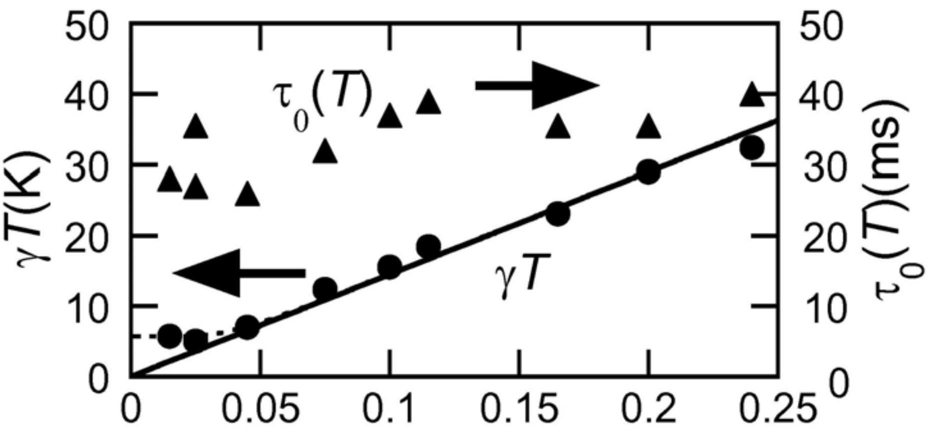


Figure 4